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ULTRAVIOLET REFLECTIVITY OF VENUS AND JUPITER

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DENNIS C. EVANS

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Dennis C. Evans

Goddard Space Flight Center
National Aeronautics and Space Administration
Greenbelt, Maryland, U.S.A.

ABSTRACT

Low resolution ultraviolet spectrograms (2300 to 3700 Angstroms) of Venus and Jupiter have been obtained using rocket borne objective grating spectrographs.

The Venus spectrum, characterized by a broad absorption-like feature beginning at 3300 Angstroms and reaching a reflectivity minimum at 2500 Angstroms, can be given at least two credible interpretations (1) The combined effects of Rayleigh scattering from a 60 millibar atmosphere above a "cloud surface" which has a reflectivity decreasing toward the ultraviolet would produce such a spectrum. (2) The spectrum could also be explained by Rayleigh scattering in an atmosphere containing $1/3$ to $1/10$ the earth's amount of ozone, combined with wavelength independent reflectivity from a "cloud surface". In the second model the effective scattering pressure altitude at 2500 Angstroms is 60 millibars, compared to 1 millibar for the earth. Compared to the earth's atmosphere and $\text{CO}_2:\text{N}_2$ model atmospheres, the ozone maximum would be near 250 millibars pressure altitude. The constant value of reflectivity near 3500 Angstroms indicates that the "cloud surface" would be at a pressure less than 1000 millibars, perhaps very close to the ozone maximum. The abundance of ozone would suggest a source other than $\text{CO}_2:\text{N}_2$ photochemistry, possibly $\text{CO}_2:\text{N}_2:\text{H}_2\text{O}$.

The Jupiter spectrum is consistent with the photoelectric spectra of that planet obtained by T. P. Stecher which he

interprets in terms of Rayleigh scattering from 10 kilometer-atmospheres of molecular hydrogen above a cloud layer (Ap. J., October 1965).

Low resolution, ultraviolet spectrograms of Venus and Jupiter were obtained using objective grating spectrographs aboard an Aerobee rocket (NASA 4.126 GG). The rocket was launched from White Sands Missile Range at 10:15 UT on 22 August 1964. The payload reached a maximum altitude of 122 kilometers, with all spectrograms being obtained at altitudes above 90 kilometers; high enough to be completely free of obscuration by the earth's ozone.

The spectrograms described in this report cover a wavelength range of 2300 to 3700 Angstroms. They were obtained using objective grating spectrographs constructed using modified Nikon, electrically driven, 35 mm cameras. The details of the spectrographs are listed in Table 1. One such spectrograph was aimed at each planet. An inertially-referenced attitude control system pointed the spectrographs. While pointing, the whole rocket oscillated slightly in a $\pm 1/4$ degree limit cycle. It was this limit cycle motion which produced the low resolution of the spectrograms: Venus, ~ 35 Angstroms; Jupiter, ~ 50 Angstroms. The spectrographs were recovered by means of a parachute which was deployed at about 20,000 feet altitude, after atmospheric drag slowed the payload to a safe speed.

Eastman Kodak type I-0, 35 mm film was used to record the spectrograms of the planets. The relationship between photographic density and light intensity for the "flight" film was determined using monochromatic 2537 Angstroms radiation from a low pressure mercury-vapor lamp. The relative response of the spectrographs was determined using mercury-xenon lamps, and tungsten-iodine lamps calibrated by the National Bureau of Standards. The spectral reflectivity data obtained were to be normalized to data available in the literature obtained using ground based and rocket borne equipment. The film was therefore calibrated in a relative sense, as opposed to absolute photometric calibration. A study of the I-0 film showed that, for relative calibration,

reciprocity failure of the film had no effect on the response of the spectrographic systems over an exposure range of 10 to 300 seconds.

In the 2000 to 3000 Angstrom wavelength region, the 35 mm spectrographs, using I-O film, were compared to an objective grating Schmidt system using SC-5 film. Theoretically, the Schmidt system had a "flat" response in that spectral region. No significant deviation from this "flat" response by the Schmidt system was noticed.

The star λ Tauri was observed in flight by the same spectrograph that observed Jupiter. Photoelectric observations of this star by T. P. Stecher (Personal communication), and of Jupiter by Mr. Stecher (1) have also been used in the determination of instrumental response. He used photoelectric observations of a free-flowing hydrogen lamp, and calibrated his equipment in vacuum. Comparison of Stecher's observational data with the spectrograms obtained on flight 4.126 GG produce the best determination of instrumental response, being on a firmer footing and also being an "in-flight" calibration. The instrumental relative response determinations are presented in Figure 1.

The best microdensitometer trace of the Venus spectrum (Figure 2) and the Jupiter spectrum (Figure 3) have been reproduced in terms of relative intensity, uncorrected for instrumental response. It is noted, however, that the spectrographs have a "flat" response between 2500 and 3000 Angstroms. The solar spectrum presented for comparison and used to determine the reflectivities of the planets has been prepared by John P. Hennes (2) from the work of Detweiler, et.al. (3); Tousey (4); and Dunkelman and Scolnik (5). The spectral resolution of the flight spectrograms has been determined by measurement of the width and depth of the solar spectral features at 2800 Angstroms. Zero order images of stars that affect the spectra of the planets are noted. In the 51 second exposure on Venus, the film is very

near the maximum photographic density above 3000A. The 10 second exposure is more reliable in that spectral region. Note that except for solar Fraunhofer structure, there are no narrow absorption features (50-100 Angstroms) in the Venus spectrum. In the Jupiter spectrum there is an absorption feature which is noticeable at 2600 Angstroms, there being an absence of features attributed to that planet otherwise.

The spectra of the planets are interpreted and presented in terms of geometric reflectivity, $p(\alpha)$, and $p(\alpha)/i(\alpha)$. These terms occur in the definition of Bond Albedo, which is defined as the ratio of the total reflected flux to the total incident flux, given by the equation

$$A_B = \frac{p(\alpha)}{\varphi(\alpha)} \cdot q \quad (1)$$

where

α = phase angle = angle between sun and earth as seen from the planet.

$\varphi(\alpha)$ = phase law = change of planetary brightness with α , at constant distance from the planet, with $\varphi(0) = 1$,

q = phase factor (a constant) $= 2 \int_0^\pi \varphi(\alpha) \sin \alpha \, d\alpha$: a factor that represents the phase law of scattering which occurs at the reflecting surface.

$p(\alpha)$ = geometric reflectivity = ratio of planet brightness to the brightness of a perfectly diffusing circular disc of the same position and apparent size as the planet. The incoming solar radiation is considered to be normal to the disc at all phase angles. (Note that all terms are also functions of wavelength so the wavelength region of interest must be specified) (6,7).

The term $i(\alpha)$, the illuminated fraction, is the ratio of the illuminated portion of the planet to the projected disc of the entire planet as viewed from earth. For a smooth sphere, $i(\alpha) =$

$\frac{1}{2} (1 + \cos \alpha)$. The ratio $p(\alpha)/i(\alpha)$ can be interpreted as the geometric reflectivity of the illuminated fraction of the planet as viewed from earth.

Prior to the experiment, it was decided to normalize all the flight data to match the ultraviolet geometric reflectivity value, U , determined by ground based observers. A disagreement has been noticed with this method for the data concerning Jupiter. The flight data for Jupiter have been normalized at 2700A, based on the work of Stecher (1) and the work of Boggess and Dunkelman (8). This produced a disagreement with the ground-based U value presented by Harris (9). Recent work by Younkin and Munch (10) and Glushneva (11), normalized to the B wavelength reflectivity (since their values do not correspond to the entire planet) indicates that a similar discrepancy exists for ground based observations.

The geometric reflectivity of Jupiter, adjusted to zero phase angle, is presented in Figure 4. The ultraviolet spectrum of Jupiter has been observed photoelectrically and analyzed by T. P. Stecher (1). The data obtained on the present rocket flight are not sufficiently different from Stecher's observations to merit a rediscussion of his results. Both sets of data follow the same trends as a function of wavelength, and both include an absorption feature at 2600 Angstroms. Stecher concludes that the spectrum is adequately explained in terms of Rayleigh scattering from approximately 10 kilometer atmospheres of molecular hydrogen above a non-reflecting cloud layer.

The reflectivity of Venus as a function of wavelength is presented in Figure 5. The geometric reflectivity values have been normalized, at the U wavelength to a value of $p(90^\circ) = 0.09$ or equivalently $p(90^\circ)/i(90^\circ) = 0.18$. The data are analyzed in terms of $p(\alpha)/i(\alpha)$. Normalization to zero phase angle was not done for two main reasons:

1. No reliable photometric observations of Venus are available for phase angles of less than 20° , since for

these low angles the angular separation of the sun and Venus is very small.

2. There are marked differences among experimenters in the extrapolation of the phase law, $\varphi(\alpha)$, to zero phase angle. These differences in "theoretical" treatment of data have serious effects on the final determination of the functions $\varphi(\alpha)$, $p(\alpha)$, and q . However, the observations in the $30^\circ \leq \alpha \leq 150^\circ$ are somewhat similar. For example, the extreme deviations from the mean value of $p(\alpha)$ used in this report are:

λ	<u>deviation%: $p(0^\circ)$</u>	<u>deviation%: $p(90^\circ)$</u>
V	± 28	± 16
B	± 35	± 8
U	± 40	± 6

The deviation at 90° phase angle is representative of experimental differences. The deviation at 0° phase angle is representative of the same experimental differences. The numerical values of reflectivity which apply to Venus, as determined by Knuckles, Sinton, and Sinton (12); Danjon (13); and de Vaucouleurs (14); and the values for certain reflectivity models presented by Schonberg (6); Harris (9); and derived in this paper are summarized for comparison in Table 3.

Spectral reflectivity values for model atmospheres with Rayleigh scattering can be evaluated using tables prepared by Coulson, Dave, and Sekera (15). Graphical integration of a series of plane parallel atmospheres tangent to each point of a spherical model planet produce reflectivity values for spherical model atmospheres. Models with 0.0 and 0.8 perfectly diffuse surface reflectivity have been prepared to show the reflectivity properties of the atmosphere itself, and the influence on the reflectivity of a highly reflective surface at the bottom of the atmosphere. These numerical values are presented in Table 2, in

terms of $p(90^\circ)/i(90^\circ) = 2 p(90^\circ)$, and not in terms of geometric reflectivity, $p(90^\circ)$.

The correspondence between wavelength, optical thickness, surface pressure, and reflectivity is presented in Figure 6. Although possible to derive this correspondence independently, the relationship has been based largely on work done by Coulson and Lotman (16) for model atmospheres consisting of 90% N_2 , 9% CO_2 , and 1% A.

The assumed composition of the Venus atmosphere is based on the identification of CO_2 absorption features in the spectrum of that planet(17). The presence of Argon and nitrogen are assumed by analogy to earth, but neither they nor any other compounds of major bulk composition importance have been identified. The most recent investigations of Venus indicate that CO_2 is a minor constituent of that planet's atmosphere (18). Unfortunately, the bulk composition of the Venus atmosphere still cannot be stated with certainty. Nevertheless, the scattering properties can be analyzed in terms of Rayleigh scattering because the variations caused by incorrect composition assumptions are small. The scattering properties of Nitrogen and Argon are similar, and in general Argon is ignored because it is expected to be such a minor component of the Venus atmosphere. An atmosphere of 90% Nitrogen behaves almost identically as an atmosphere of 100% Nitrogen. For a molecular atmosphere of pure CO_2 the pressure values derived will be about seven tenths of the pressures for the 90% N_2 , 9% CO_2 , 1% Argon atmosphere used in this report. Since there is little significant influence of composition on the interpretation presented in this report, the assumption of 90% N_2 , 9% CO_2 and 1% A was used throughout.

One of the main considerations at the start of this experiment was that it should have been possible to detect ozone on Venus. Unfortunately, the spectral information obtained will not permit a clear-cut interpretation. There are two ways that the Venus

ultraviolet spectrum can be given a reasonable interpretation. The first possibility is that the reflectivity is a combination of scattering from the atmosphere and reflectivity from the cloud surface. The second possibility is similar, except that ultraviolet absorption due to ozone is assumed.

A. Reflectivity Explained by "Cloud Surface" Absorption and Atmospheric Scattering, with no Absorption in the Atmosphere

Combination, by addition, of the reflectivity values of a 60 millibar atmosphere (interpolated from Figure 6) and an assumed cloud reflectivity spectrum, will nearly match the Venus spectral data. This model representation is graphically presented in Figure 7. The cloud composition is assumed to be H₂O-ice crystals based on the work of Strong and others (19, 20).

Although the simplicity of this explanation is appealing, there are difficulties which cannot be easily explained. The reflectivity decrease in the ultraviolet cannot be explained by spectral absorption of H₂O since the absorption coefficient for H₂O is small in that spectral region. Mie scattering effects caused by ice "droplets" of selected sizes near and below one micron might account for the reflectivity decrease, but such "droplet" sizes are rare on earth (21,22). Even if rarity on earth is considered, the upper altitude limits of ice crystal clouds would be an ideal location for such very small ice particles.

The reflectivity decrease might possibly be explained by chemical contaminants in the clouds, but a specific compound has not been found that will reproduce such a characteristic spectrum and not be identifiable elsewhere in the spectrum of Venus.

B. Reflectivity Explained by Atmospheric Scattering, Ozone Absorption, and Reflection from the Cloud Surface

Based on the known absorption properties of ozone and the calculable scattering properties of molecular atmospheres, the ultraviolet spectrum of Venus can be synthesized by an appropriate model planetary atmosphere containing ozone.

There is one major assumption made in order to proceed with a description of the Venus spectrum: That is, the cloud surface must have a reflectivity that is independent of wavelength in the 3000 to 3500 Angstrom region of the spectrum. The identification of H_2O on Venus resulting from the infrared observations of that planet by Strong et.al., (19, 20), lends credence to the wavelength independent assumption because the absorption coefficient of H_2O in the required spectral region is very small and independent of wavelength.

In order to estimate the amount of ozone that may be present in the atmosphere of Venus, it is necessary to determine the "effective thickness" of the proposed ozone layer. The integration of optical pathlength of light incident to and reflected from the cloud surface, for a single traverse, has been carried out graphically for a spherical shell at 90° phase angle. For a layer of unit vertical thickness; the average single traverse pathlength is 6.24 times the vertical thickness. Weighing the "effective path" according to the relative illumination of a perfectly diffusing sphere at 90° phase angle, the pathlength becomes somewhat shorter, about 4.2 times the vertical thickness. The difference in these two pathlength approximations has negligible influence on interpretation of absorption in the "wings" of the ozone band. The total abundance of ozone was determined by comparing the shape of the Venus spectrum to the shapes of the absorption curves for various amounts of ozone in the 3000 to 3500 Angstrom region, where the total absorption is low and the cloud surface reflectivity is high. Ozone abundances from 0.0001 to

0.3 centimeter-atmospheres were investigated, with the best fit occurring for 0.1 to 0.03 centimeter-atmospheres of ozone. This is 1/3 to 1/10 of the amount of ozone found in the earth's atmosphere.

In order to match the reflectivity values for Venus in the spectral region where ozone is totally absorbing, it is convenient to make a comparison of the earth's atmosphere with the atmosphere of Venus. An empirical relationship has been found to exist between the "effective scattering pressure" and the transmission of light through ozone in the earth's atmosphere. The reflectivity of the earth's atmosphere can be represented by scattering from a model in which the pressure is taken as the pressure-altitude where $1/e$ of the incoming radiation, at any wavelength, is absorbed by ozone (23, 24). This relationship has been applied to Venus in the interpretation of the distribution of ozone in the atmosphere of that planet. The spectrum of Venus was arbitrarily matched and the pressure-altitude corresponding to each wavelength was noted using the pressure-reflectivity correspondence presented in Figure 6. Based on the " $1/e$ " comparison, it is noted that the effective scattering level for 2500-2600 Angstrom radiation is about 60 millibars for Venus, compared with 1 millibar for the same spectral region in the earth's atmosphere. The effective pressure-altitudes determined at 2400-2800 Angstroms and 2300-2900 Angstroms (symmetrically located about the ozone absorption maximum) indicate that the ozone abundance is increasing with depth into the Venus atmosphere about two times as fast as the abundance increase in the earth's atmosphere.

Based on the work of Marmo and Warneck (25) for $\text{CO}_2:\text{N}_2$ model atmospheres of the planet Mars, it is apparent that $\text{CO}_2:\text{N}_2$ photochemical equilibrium will not produce an ozone layer that is so deep in a planetary atmosphere. An alternative source for the ozone must therefore be proposed. To do this, the altitude of the ozone maximum must be estimated. In the earth's

atmosphere, the distance between the effective reflecting layer at 2500-2600 Angstroms and the ozone abundance maximum is about 25 kilometers. Since the ozone abundance gradient for Venus is about twice that of earth, and the total abundance is less for Venus than earth, the similar separation distance for Venus is estimated at 10 to 12 kilometers. This altitude difference implies a pressure of about 250 to 300 millibars for the ozone maximum. It is interesting to note that this pressure- altitude corresponds nearly to that proposed for the cloud surface (26, 27). Also, because the reflectivity of Venus is nearly wavelength independent in the 3300-3700 Angstrom region it appears that the cloud surface is at a pressure altitude of less than 1000 millibars. It does not appear illogical to assume therefore that there is a "close" relationship between the ozone maximum and the cloud tops. Although the kinetic chemistry of production of ozone from H_2O has not been evaluated, such an equilibrium is possible (28). Since the proposed model environment permits penetration of 1900 to 2100 Angstrom radiation to the cloud "surface", and since photodissociation of H_2O is assumed to account for the relative absence of H_2O from Venus, the H_2O clouds may be the source of the ozone layer.

The O_3/O_2 equilibrium ratio calculated by Marmo and Warneck (25) for Mars was applied to Venus with the conclusion that there may be 50 to 150 centimeter-atmospheres of O_2 present on Venus. This abundance of O_2 is about equal to the upper limit for that molecule set by Spinrad and Richardson (18). Thus, the proposed ozone values are not inconsistent with other spectrograms of Venus.

The ozone absorption model is graphically summarized in Figure 7. (Along with the no-ozone model). Also the graphical representation of a model atmosphere with about 0.1 centimeter-atmospheres of ozone, the ozone maximum being at 1000 millibars, is illustrated in Figure 7 to show the pressure effects in the

model. The reflectivity values for all the models are extended to 2000 Angstroms. In the wavelength region shorter than 2300 Angstroms, it should be possible to distinguish between the various models presented in this paper.

In reality the description of the Venus' atmosphere will always necessitate basic assumptions about parameters such as "cloud reflectivity" or "bulk chemical composition", as long as observations must be made with earth based equipment. Thus, the actual atmosphere may perhaps be approximated by a continuum of models chosen between the ones described in this report. The present models can therefore be considered as limiting descriptions of the ultraviolet spectrum of the planet Venus.

Table 1

OBJECTIVE GRATING SPECTROGRAPHS

Modified 35 mm Camera

Aperture	25 mm
Effective focal length	90 mm
Geometric focal ratio	f/3.6
Effective focal ratio	~ T/4.0
Objective Grating	
lines	600/mm
spacing	1.667 microns
Film format	24 x 35 mm
	(flat surface)
Film capacity	36 exposures
Transmission elements	2 silica lenses
	2 CaF ₂ lenses
Reflective elements	1 diagonal mirror
	MgF ₂ coating
Angular resolution	~ 0.25°
Spectral resolution	~ 10 Å
Nominal dispersion	111 Å/mm
Film type	Eastman I-O
Spectral range possible	2350Å to 4500Å
(film sensitivity limits)	
Spectral Range (Flight 4.126 GG: film format limits)	2350Å to 3700Å

Table 2

Reflectivity, $p(\alpha)/i(\alpha)$, of a Planet with a Rayleigh
Scattering Atmosphere at 90° Phase Angle*

Normal Optical Thickness	Perfectly Diffuse Surface Reflectivity	
	0.0	0.8
0.00(a)	0.000	0.339
0.02	0.008	0.34
0.05	0.020	
0.10	0.035	
0.15	0.044	
0.25	0.070	
0.50	0.115	
1.00(b)	0.175	0.32
2.00(b)	0.23	
3.00(b)	0.26	
4.00(b)	0.27	
5.00(b)	0.28	
Infinite(a)	0.31	0.31

* based on the work of Coulson, Dave, and Sekera (15)

(a) based on the work of Harris. (9)

(b) interpolated.

Table 3

ALBEDO PARAMETERS OF VENUS AND MODEL PLANETS

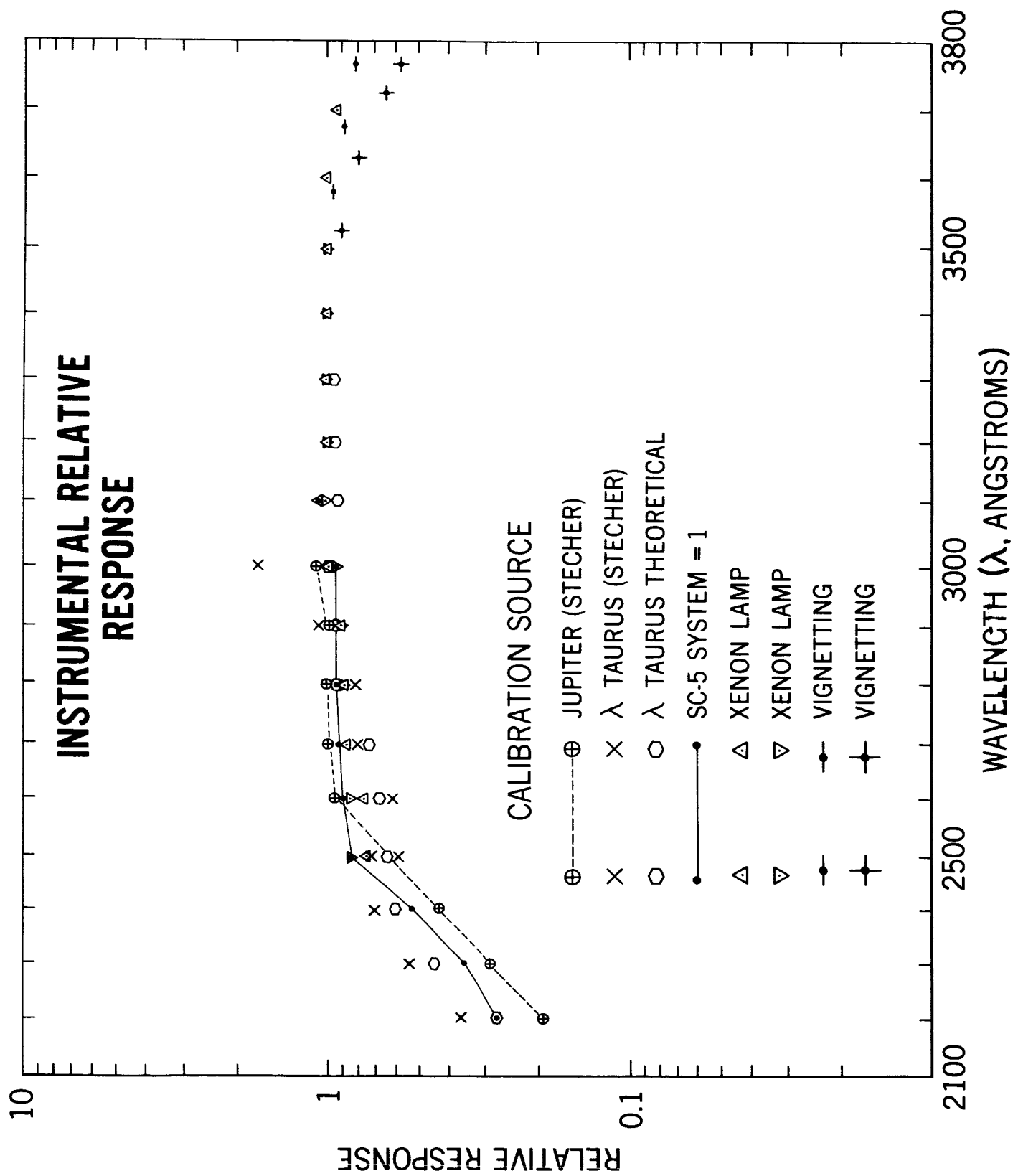
	Wavelength	$p(0^\circ)$	$p(90^\circ)$	$\frac{p(90^\circ)}{p(0^\circ)} = 2p(90^\circ)$	q	A_B	Ref.
Venus	V	.985	.168	.336	.888	0.87 ± 0.04	(12)
	V	.548	.185	.370	1.296	0.71	(13)
	V	.650	.133	.266	1.087	0.705	(14)
	V	.586	.14	.28	1.296	0.76	(13)
Lambert Sphere	any	.667	.212	.424	1.5	1.0	(6)
	any	.534	.170	.339	1.5	.8	(6)
Model 0.3 ^a	V	.56	.17	.34	-	-	This paper
Model 0.0 ^a	V	.07	.015	.030	-	-	This paper
Venus	B	1.026	.142	.284	.763	0.78 ± 0.05	(12)
	B	.492	(.12) ^b	(.24) ^b	-	-	(13)
Model 0.8	B	.59	.17	.33	-	-	This paper
Model 0.0	B	.15	.033	.065	-	-	This paper
Venus	U	.810	.096	.193	.649	0.53 ± 0.06	(12)
	U	.353	(.085) ^b	(.17) ^b	-	-	(13)
Model 0.8	U	.62	.16	.33	-	-	This paper
Model 0.0	U	.24	.058	.12	-	-	This paper
Infinite Rayleigh	any	.798	.192	.384	1.25	1.00	(9)

(1)a The Models 0.8 and 0.0 represent a 1000 mb atmosphere, graphically derived from the work of Coulson, Dave, and Sekera. (15)

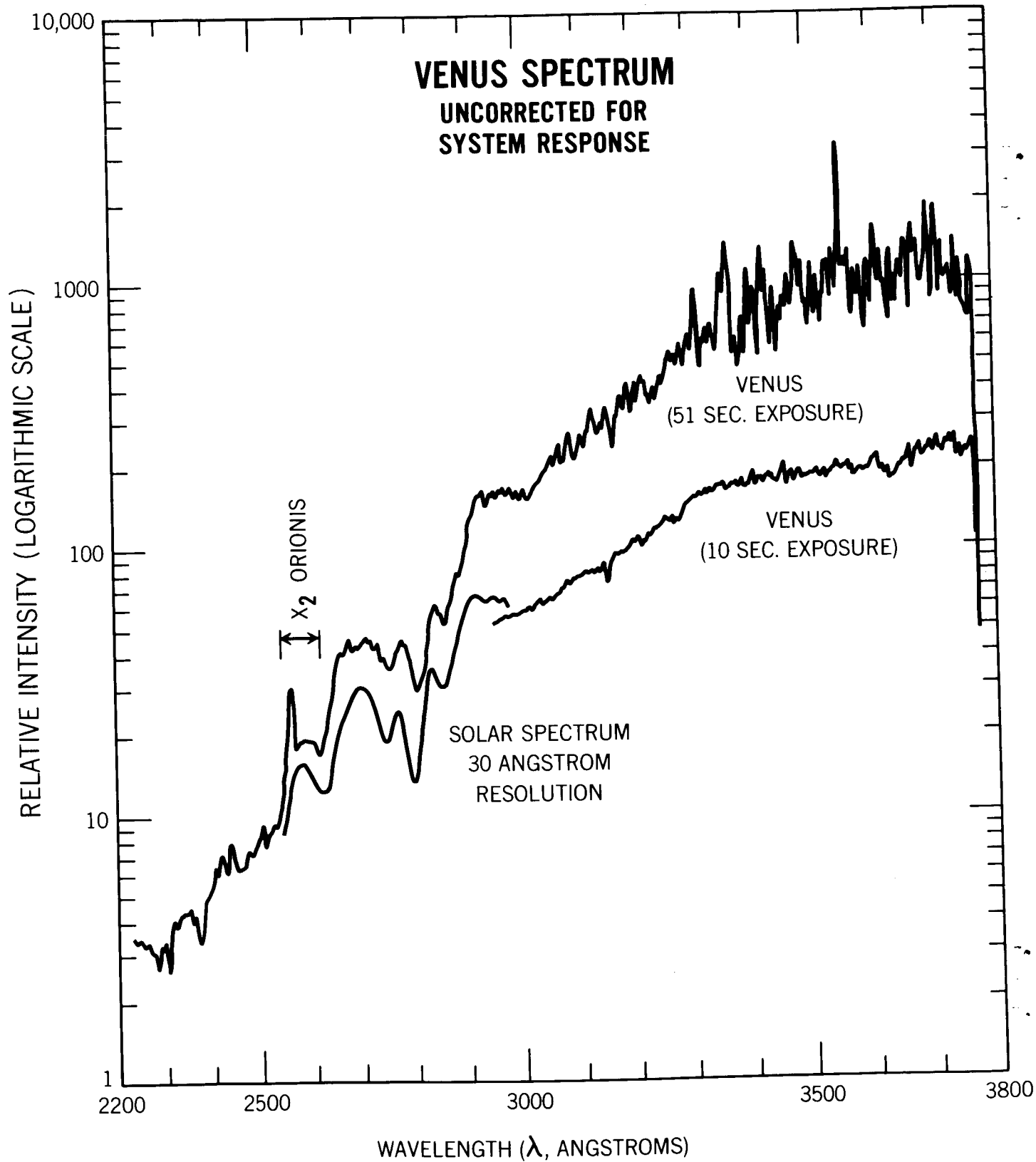
(2)b The values for $\alpha = 90^\circ$ are derived using the visual values for $\varphi(\alpha)$, presented by Harris. (9)

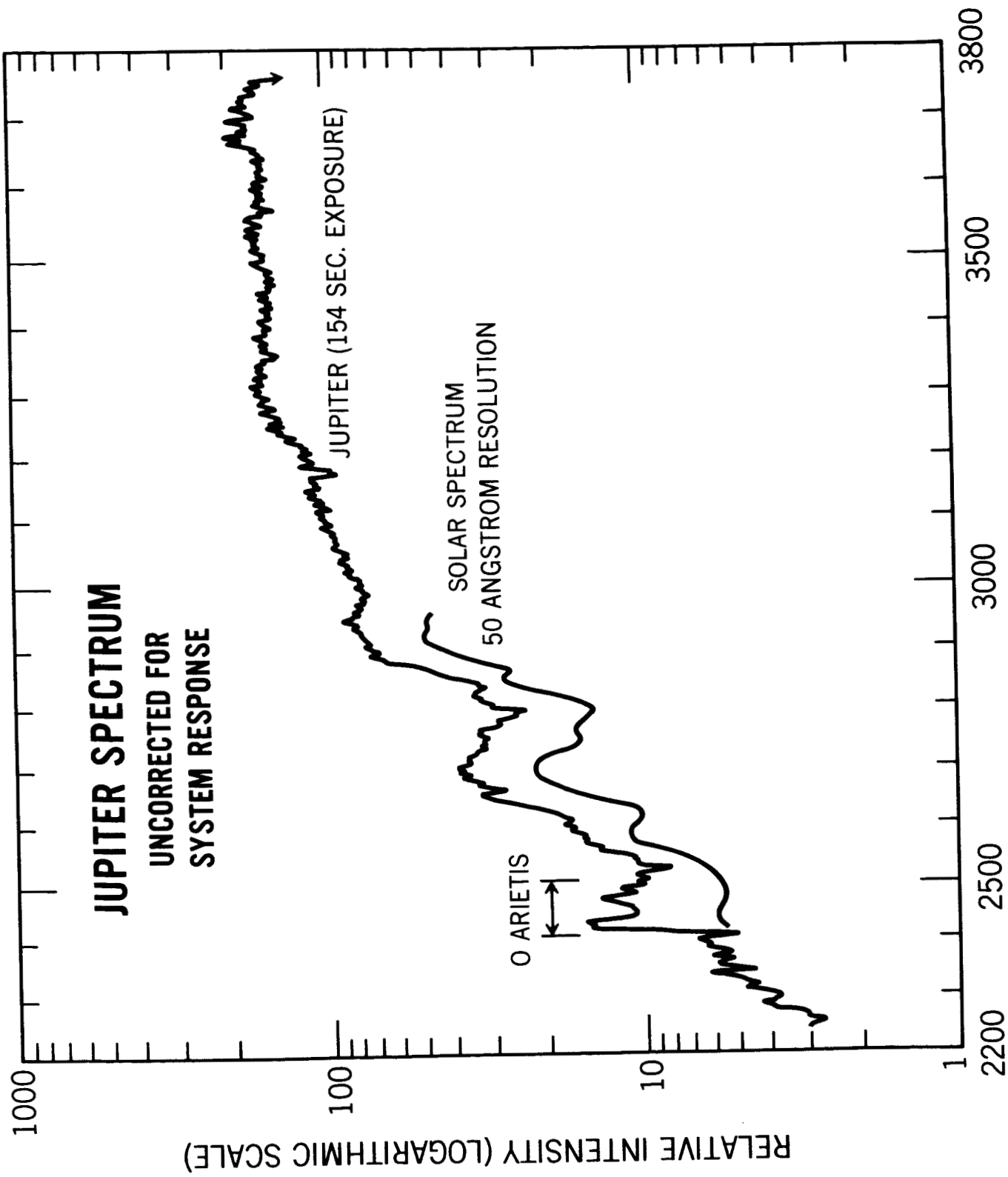
LIST OF FIGURES

1. Instrumental Relative Response
2. Venus Spectrum, uncorrected for system response
3. Jupiter Spectrum, uncorrected for system response
4. The Geometric Reflectivity of Jupiter
5. The Geometric Reflectivity of Venus
6. Reflectivity of Model Venus Atmospheres
7. Reflectivity Models to Match Venus Data

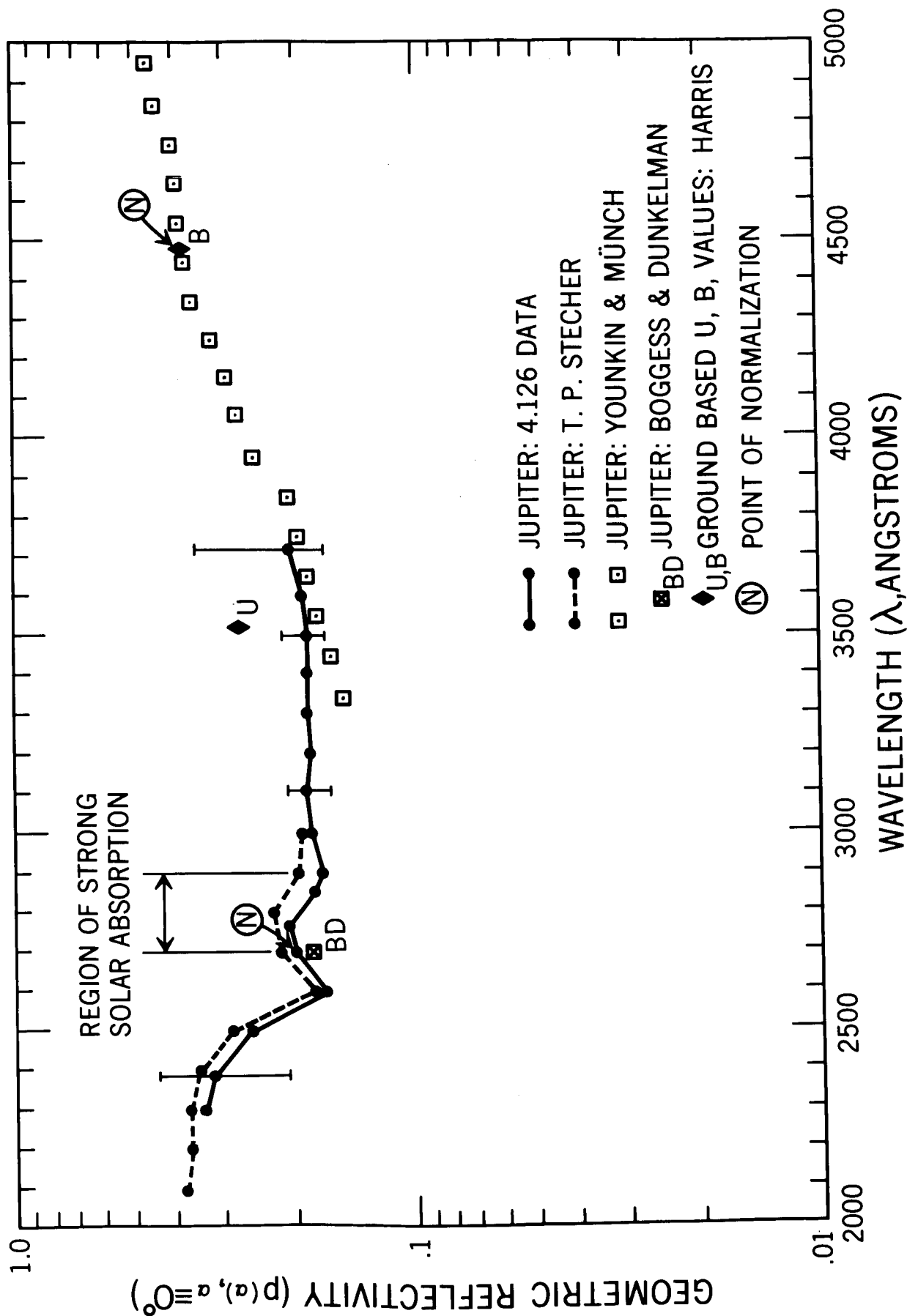


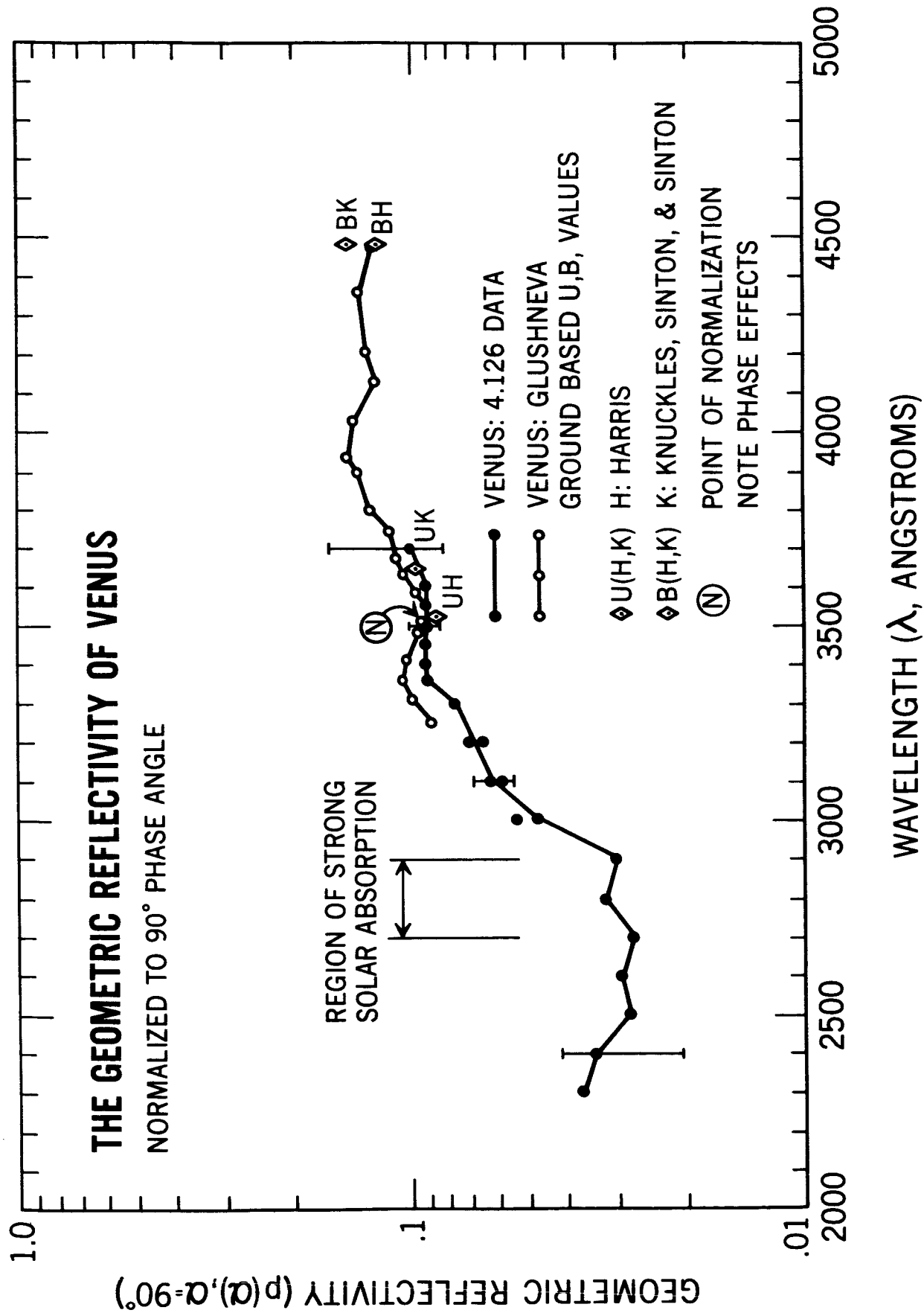
VENUS SPECTRUM UNCORRECTED FOR SYSTEM RESPONSE





THE GEOMETRIC REFLECTIVITY OF JUPITER





SURFACE REFLECTIVITY : 0.0
 COMPOSITION : 90% N₂, 9% CO₂, 1% A

REFLECTIVITY ($p(\alpha)/i(\alpha)$, $\alpha = 90^\circ$)

SURFACE PRESSURE

1000 mb
 600
 350
 230
 150 mb
 85
 50
 30
 20 mb

INFINITE

WAVELENGTH (λ , ANGSTROMS)

COMPOSITION : 90% N₂, 9% CO₂, 1% A

1000 mb

600

350

230

150 mb

58

50

30

20

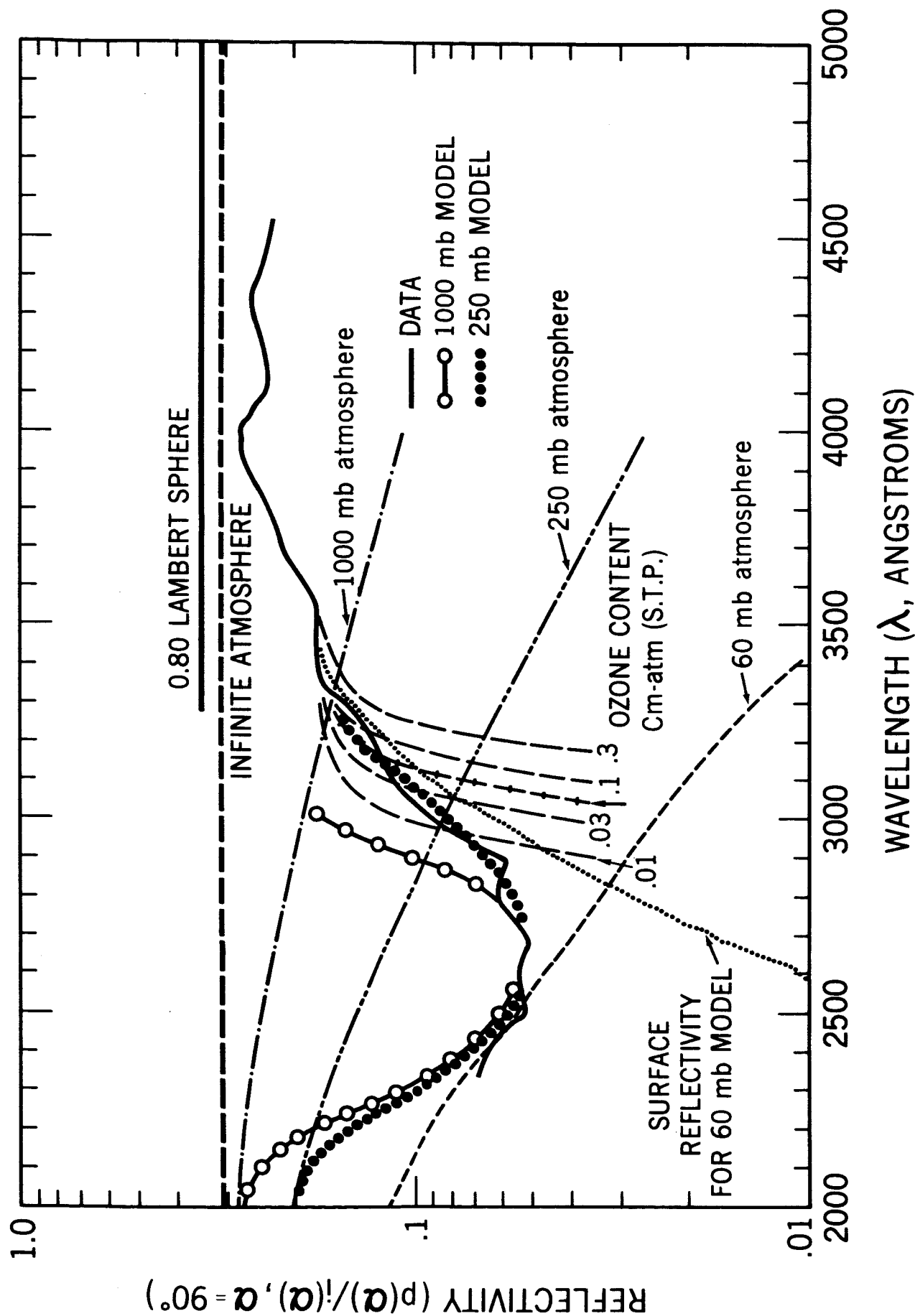
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74

WAVELENGTH (λ , ANGSTROMS)

REFLECTIVITY MODELS TO MATCH VENUS DATA



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